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# SIMULATION DE LA RÉTRODIFFUSION RADAR D'UN MANTEAU NEIGEUX. COMPARAISON AVEC LES DONNÉES DU PROJET NOSREX.

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## 1. INTRODUCTION

This paper presents a multilayer snowpack electromagnetic backscattering model, based on Dense Media Radiative Transfer (DMRT). This model is capable of simulating the interaction of electromagnetic wave (EMW) at X-band and Ku-band frequencies with multilayer snowpack. The air-snow interface and snow-ground backscattering components are calculated using the Integral Equation Model (IEM) by [1], whereas the volume backscattering component is calculated based on the solution of Vector Radiative Transfer (VRT) equation at order 1. Case study has been carried out using measurement data from NoSREx project [2], which include SnowScat data in X-band and Ku-band, TerraSAR-X acquisitions and snowpack stratigraphic in-situ measurements. The results of model simulations show good agreement with the radar observations, and therefore allow the DMRT model to be used in various applications, such as data assimilation [3].

## 2. DENSE MEDIA RADIATIVE TRANSFER FOR MULTILAYER SNOWPACK

The DMRT model, based on the solution of VRT equation at order 1, simulates the multilayer snowpack backscattering coefficient in three components:

$$\sigma_{sim} = \sigma_{as} + \sigma_v + \sigma_g \quad (1)$$

where:

- $\sigma_{as}$  represents the air-snow interface backscattering, calculated using the Integral Equation Model (IEM) [1].
- $\sigma_v$  represents the snowpack volume backscattering, calculated by resolving the VRT equation [4].
- $\sigma_g$  represents the snow-ground interface, calculated using the IEM while taken into account the attenuation of snow on the ground.

The physical parameters of a multilayer snowpack such as thickness, snow density and optical grain diameter of each layer are taken into account in the calculation of each layer's effective permittivity  $\varepsilon_{eff}$ , which is based on the Strong Fluctuation Theory (SFT). Detailed equations can be found in [5]. Next, the extinction coefficient  $\kappa_e$  can be derived:  $\kappa_e = 2k_0 \text{Im}(\sqrt{\varepsilon_{eff}})$ . This factor is then used in the calculation of various scattering mechanisms occurring during the propagation of EMW through a multilayer snowpack, which can be categorized into 4 types: (1) transmission between two layers, (2) attenuation by the snow particles, (3) scattering and (4) coherent recombination.

Considering a snowpack made of  $n$  distinct layers, where  $\theta_k$  is the incidence angle and  $d^k$  is the thickness of layer  $k$ , the total contribution of the volume backscattering mechanism  $\sigma_v$  can be written as follows:

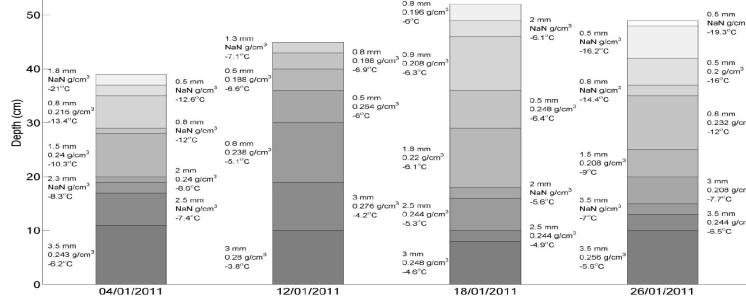
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$$\sigma_v = 4\pi \cos \theta_0 \sum_{k=1}^n \mathbf{Att}_{up}(k-1) \mathbf{T}_{(k-1)k} \frac{1 - \exp\left(-\frac{2\kappa_e^k d^k}{\cos \theta_k}\right)}{2\kappa_e^k} \mathbf{P}^k \mathbf{T}_{k(k-1)} \mathbf{Att}_{down}(k-1) \quad (2)$$

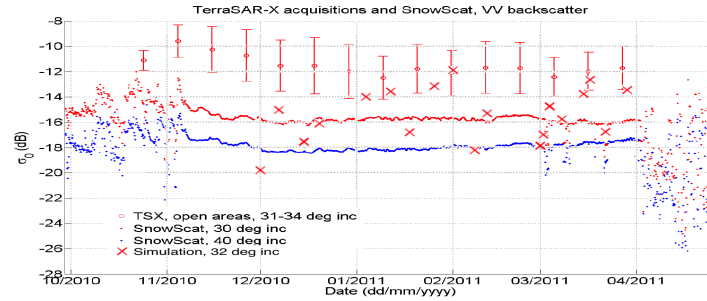
where  $\mathbf{Att}$  represents the attenuation matrix,  $\mathbf{T}$  represents the Fresnel trasmission matrix and  $\mathbf{P}$  represents the phase matrix. The expressions of these factors can be found in [3].

### 3. VALIDATION OF MODEL USING DATA FROM NOSREX PROJECT



**Fig. 1.** Example of snowpack stratigraphic profiles measurements (projet NoSREx [2]).

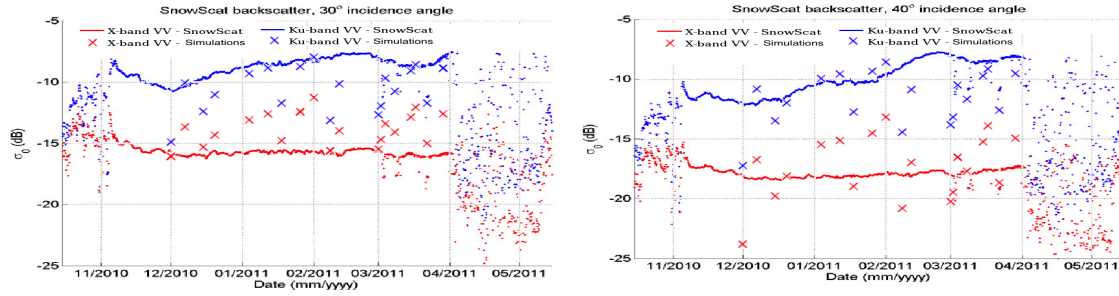
In this study, data (Figure 1) from NoSREx project [2] are used to evaluate the DMRT model. In the following comparisons, it is worth mention that the snowpack stratigraphic profiles in the NoSREx project are not taken directly at the SnowScat radar footprint and the spatial variability of the snow stratigraphy is high. Consequently, the observations can only be used as a global reference of the evolution of snowpack and not as a precise reference of the snowpack conditions which are measured by the radar. On the other hand, the snow grain size is measured using visual analysis, which can suffer from human errors. In order to obtain the optical snow grain size to be used in the EBM, we have divided the measured snow grain size by a factor equal to 2.2 (experimental value).



**Fig. 2.** Comparison of the backscattering coefficients  $\sigma_0$  observed by SnowScat at X-band frequency, TerraSAR-X and simulation of the EBM using in-situ snowpack stratigraphic measurements (project NoSREx).

Figure 2 represents the comparison of the backscattering coefficients  $\sigma_0$  observed by SnowScat at X-band frequency, TerraSAR-X and simulation of the EBM using in-situ snowpack stratigraphic measurements (project NoSREx). It can be observed that the simulated backscattering coefficients (red cross) varies around the backscattering coefficients measured by SnowScat. The high variations in the value of simulated backscattering coefficients are due to the high sensivity of the DMRT model to the optical grain diameter. The tendencies of EBM simulations and SnowScat measurements seem to agree well in the period of early March. However, we cannot reach a conclusion with respect to SnowScat and TerraSAR-X data, due to the large spatial variation of snowpack conditions.

Figure 3 Comparison of the backscattering coefficients  $\sigma_0$  observed by SnowScat at X-band and Ku-band frequencies and simulation of the EBM using in-situ snowpack stratigraphic measurements. By observing the X-band simulations and



**Fig. 3.** Comparison of the backscattering coefficients  $\sigma_0$  observed by SnowScat at X-band and Ku-band frequencies and simulation of the EBM using in-situ snowpack stratigraphic measurements (project NoSREx), at incidence angles of 30° (left) and 40° (right).

observations (red cross and red line), it can be noted that the values of simulated backscattering coefficients at incidence angle of 30° are higher than observations, whereas at 40° the values of simulations are more scattered around the values of observations. This may be due to the simulation value of snow-ground interface backscattering  $\sigma_g$  is higher when the incidence angle is low. In Ku-band, the simulations and the observations seem to show a similar tendency, especially on the period of January 2011 and early March 2011, where the tendencies are almost identical.

#### 4. CONCLUSION

In conclusion, the DMRT simulations of backscattering coefficients and observations from ground-based radar SnowScat as well as TerraSAR-X satellite show the same tendencies at certain series of measurements, despite the high standard deviation of the simulated backscattering coefficients due to high spatial variability of snowpack measurements. The validation of this DMRT model can establish a relation between SAR observations and snow stratigraphic measurements (or physical model of snowpack evolution), which allows the development of different approaches, such as data assimilation of SAR data into a detailed snowpack model [3]. These promising results also suggest the necessity of an experimental platform that allows the measurements automatically and continuously of ground-based radar, couple with regular observation of the snowpack evolution and SAR satellite acquisitions, in order to validate the electromagnetic model as well as physical models of snowpack evolution.

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